ttH at ILC

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based on the paper Phys.Rev.D.84 (2011) 014033,
done by R.Yonamine, K.Ikematsu, T.Tanabe, K.Fujii, Y.Kiyo, Y.Sumino, HY,

and further advanced studies by T.Tanabe, R.Yonamine, K.Fujii, T.Price, N. Watson, H. Tabassam, V. Martin, P.Roloff, J. Strube.

Snowmass Energy Frontier Workshop, BNL, 4/3-6 2013

Outline :

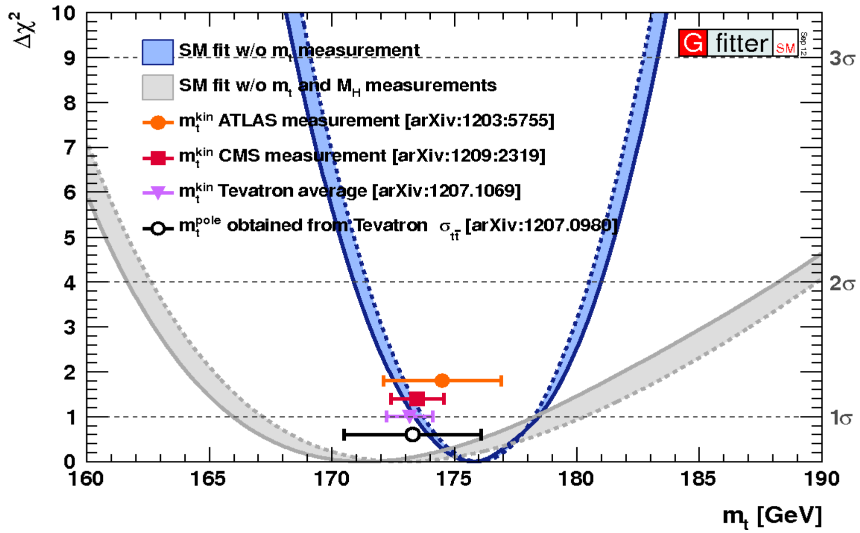
1. Introduction
2. ttH production at the ILC
3. Simulation study at /s = 500 GeV
4. Simulation study at /s = 1 TeV
5. Summary

Introduction

- Top-quark and Higgs-boson are the two main features at the ILC

These are already known to exist.

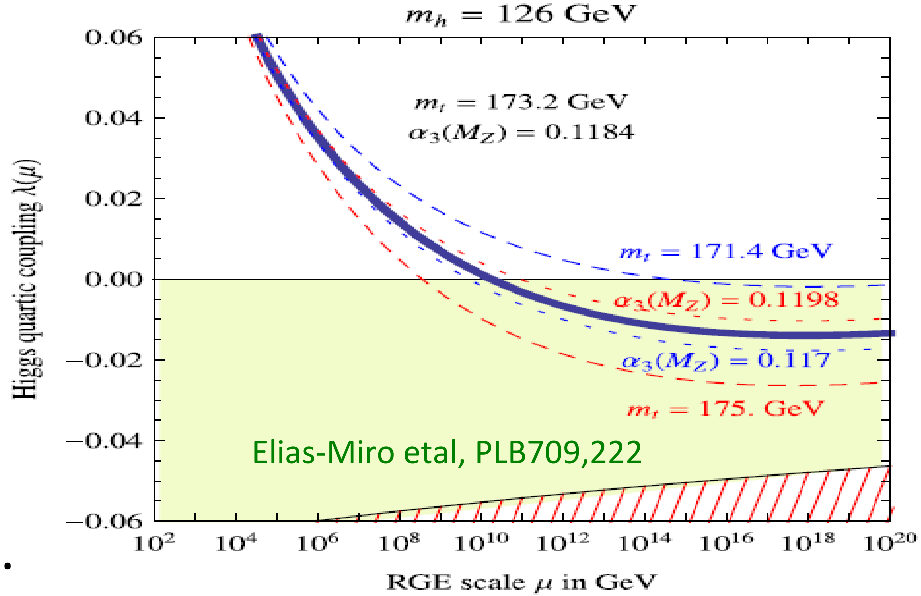
For these topics, it is very important to study and prepare what can be probed at the ILC.



- Top-quark physics: $m_t,\ y_t,\ \Gamma_t,\ \alpha_s$

Especially, precision measurement of the mass is important for

- electroweak precision tests
- stability of the EW vacuum
- possible window to new physics (y_t~1)



to disentangle the evidence of physics BSM.

Introduction

- Mass determination:

(TeV 8.7 fb[-1]) $m_t = 173.20 \pm 0.51(\text{stat}) \pm 0.71(\text{syst})\ \text{GeV}$

(LHC 4.9 fb[-1]) $m_t = 173.3 \pm 0.5(\text{stat}) \pm 1.3(\text{syst})\ \text{GeV}$

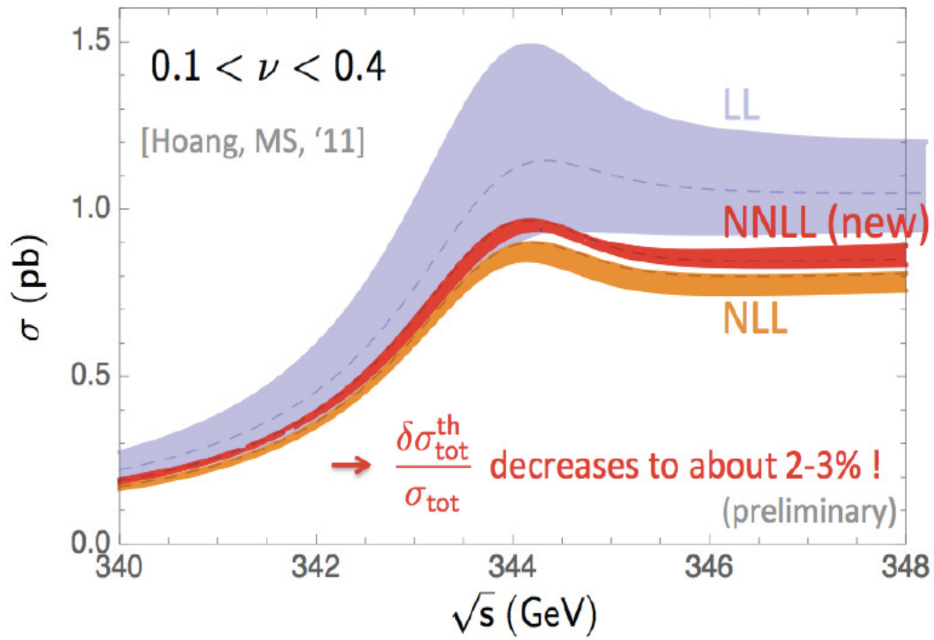
large syst. error due to mainly the Jet energy scale,
definition of the mass unclear.

At the ILC, by performing threshold scan,

$$\delta m_t \simeq 30 - 50\ \text{MeV}$$

(short distance mass),
easily converted to the MSbar mass

$$\delta m_t(\overline{\text{MS}}) \simeq 100\ \text{MeV}$$



Introduction

- Top-Yukawa measurements:

$$y_t = \frac{\sqrt{2} m_t}{v} = 0.995...$$

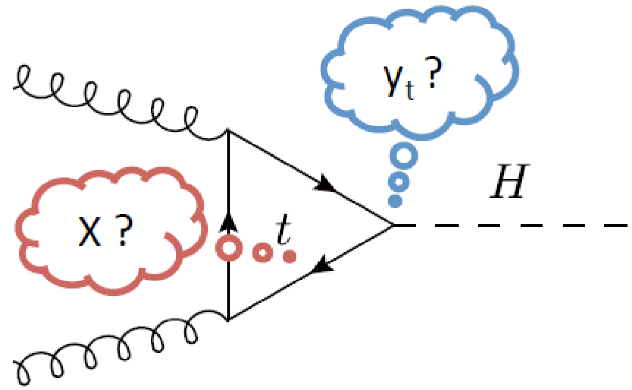
➢ Indirect: ggH (LHC)

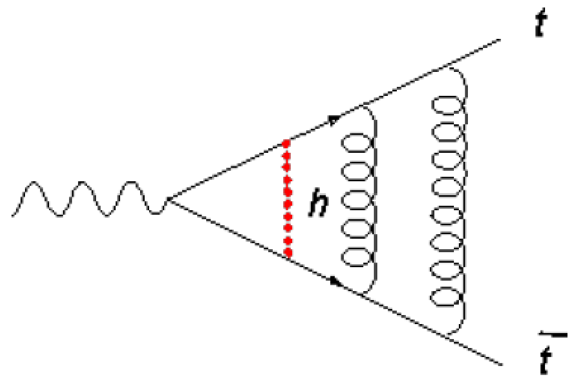
ttbar at threshold

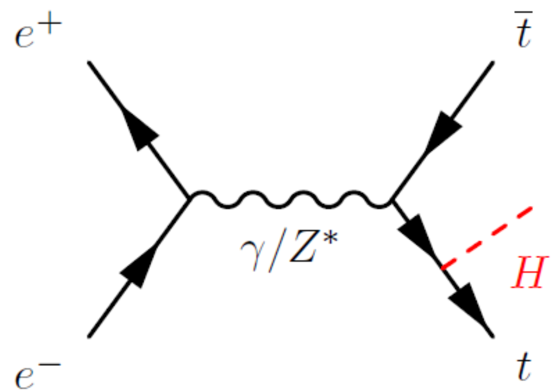
(ILC, /s=350GeV)

➢ Direct: ttH (LHC, ILC /s>500GeV)

Indirect determination is not conclusive
nor accurate, but able to check the consistency.



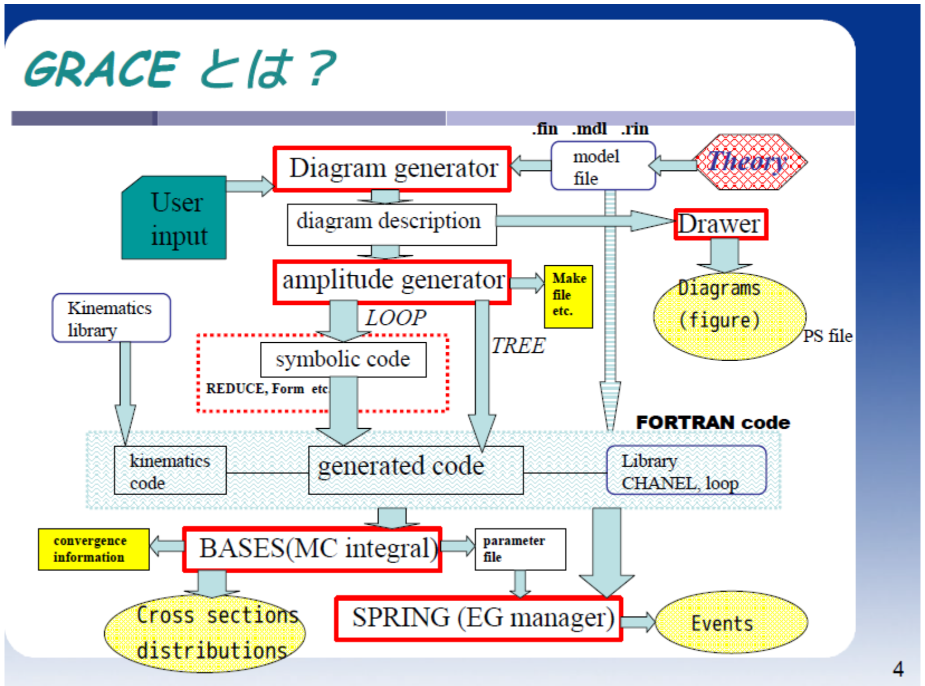


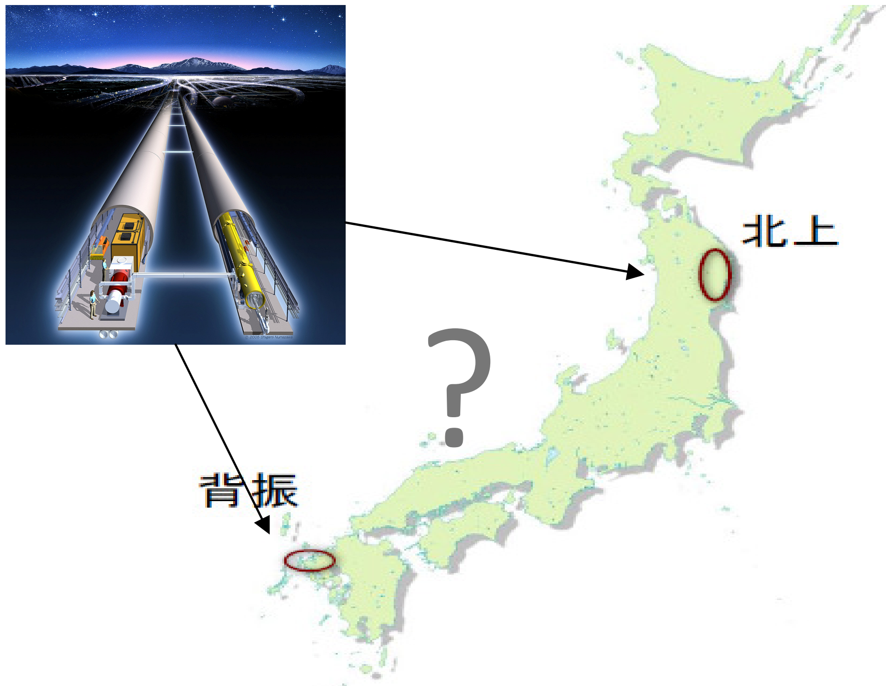


Introduction

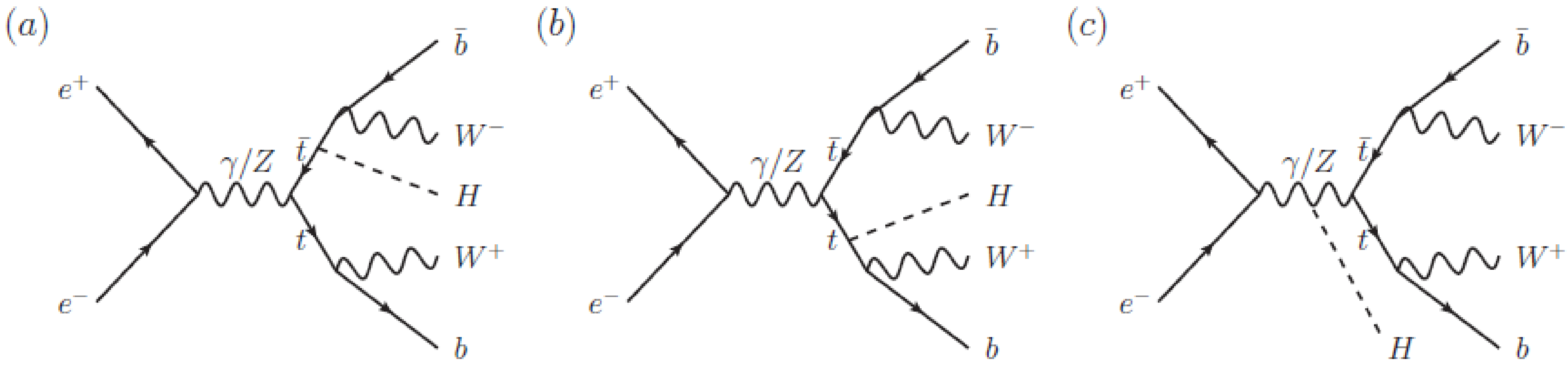
Japanese contributions to the Top-quark and ILC Physics

- **ILC Physics Subgroup** http://www-jlc.kek.jp/subg/physics/ilcphys/
- **GRACE Project (Minami-Tateya)** http://www-sc.kek.jp/
- Top-QCD theorists: **Y.Sumino, Y.Kiyo,,,**





tth process at the ILC



dominated, proportional to y_t

suppressed

$$\sigma_{t\bar{t}h} \propto y_t^2$$

$$\boxed{\frac{\Delta y_t}{y_t} = \frac{1}{2}\frac{\Delta\sigma}{\sigma}}$$

tth process at the ILC

- Signatures, using h → bb

$$e^+e^- \to t\bar{t}h \to bjj\bar{b}jjb\bar{b} \qquad \text{(8j)}$$
$$\to b\ell\nu\bar{b}jjb\bar{b} \qquad \text{(6j+l)}$$

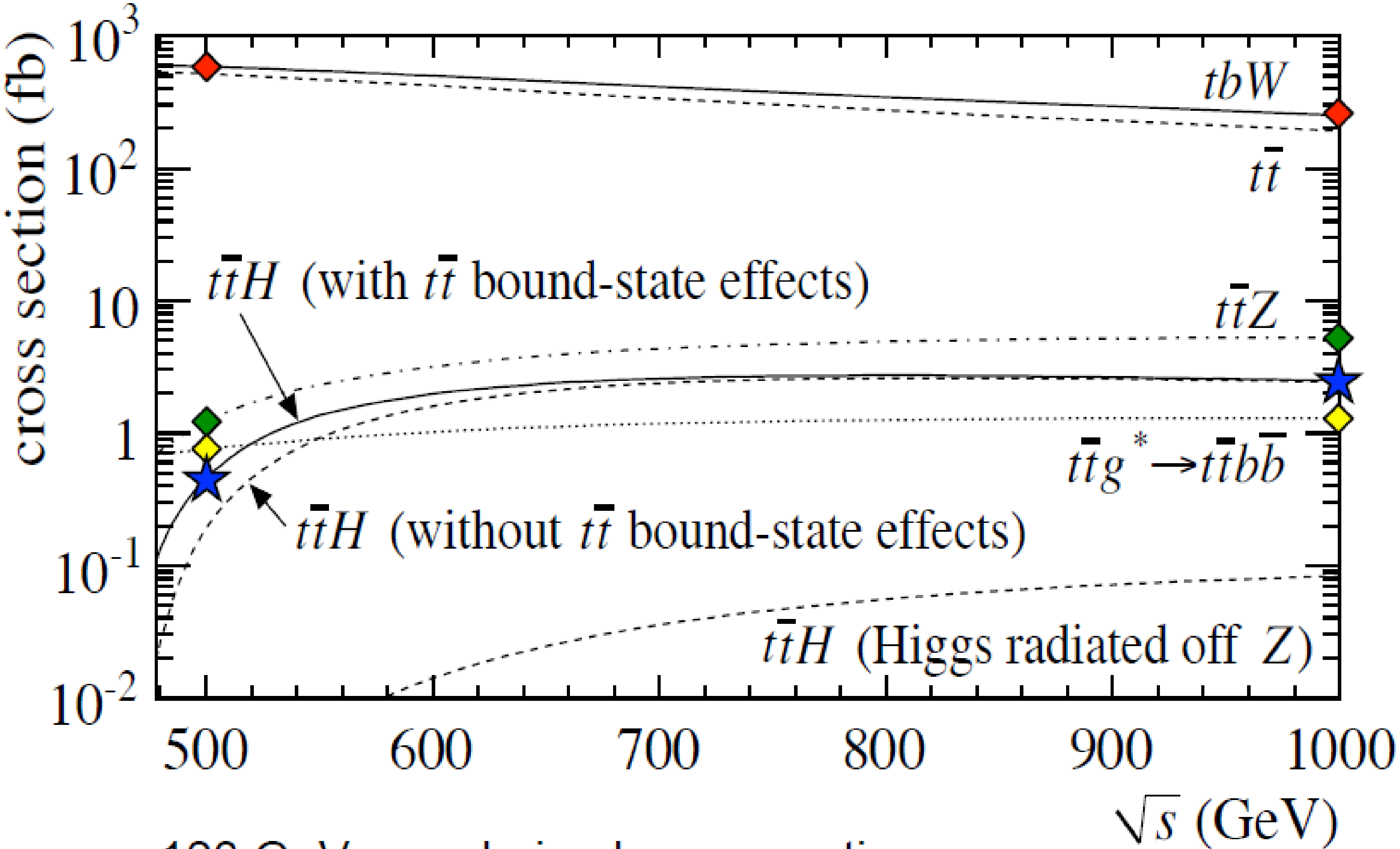
- SM Backgrounds:

$t\bar{t}Z, \quad t\bar{t}g^*$ where $Z, \ g^* \to b\bar{b}$ (irreducible)

$t\bar{t} \ (tbW)$ (large cross-section)

tth process at the ILC

ttH, ttZ, ttg*, tt



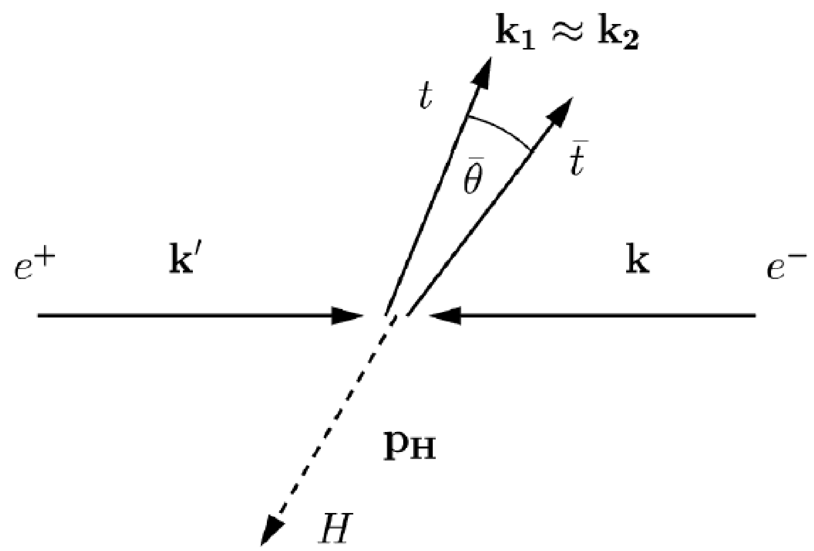
m_H = 120 GeV, unpolarized cross sections

Threshold correction

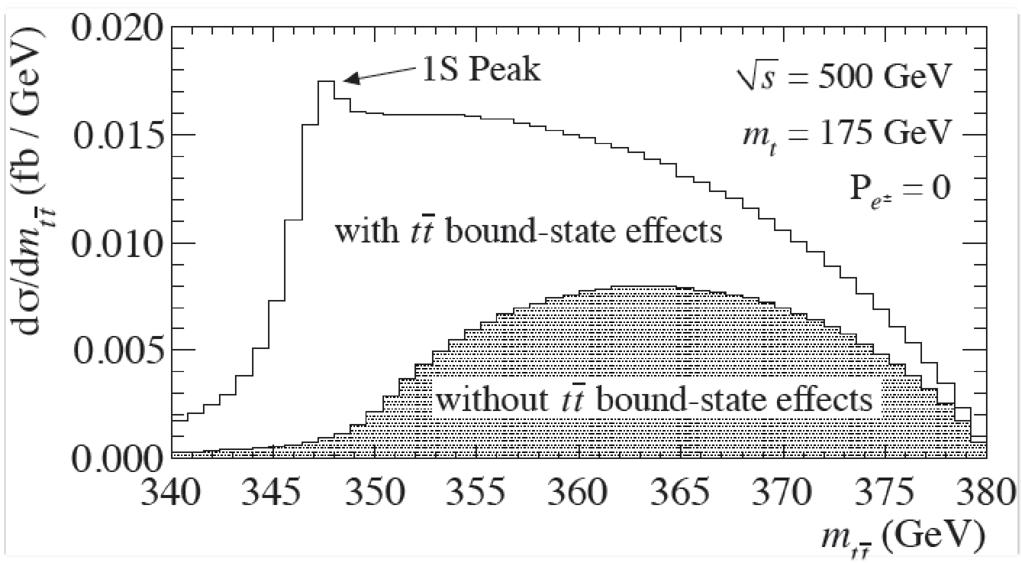
Farrel, Hoang(05,06)

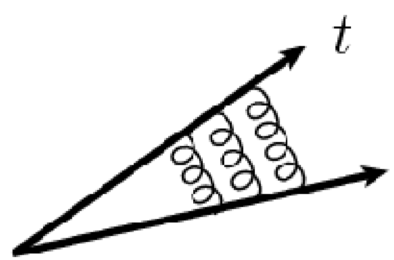
- At /s=500 GeV, threshold correction is large

$$E_h = \frac{1}{2\sqrt{s}}\left(s + m_h^2 - m_{t\bar{t}}^2\right)$$



The cross-section is enhanced by a factor of ~ 2, from the ttbar final-state interactions (bound-state effect).



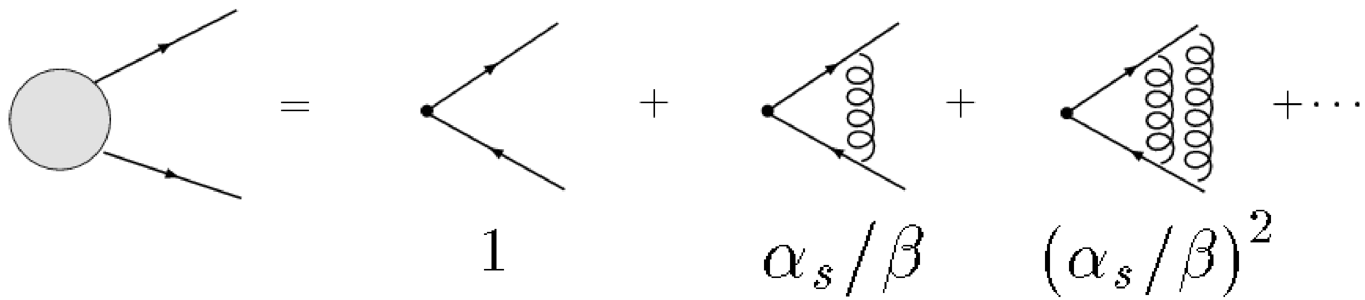


- ttZ background is also enhanced by a factor ~ 2.

Threshold correction

Fadin,Khoze(87),,,

$$\sigma \propto \mathrm{Im}[G(\vec{0}, E_{t\bar{t}})]$$



- Coordinate-space Green's function at the origin
- Sum-over the ladder diagrams nonperturbatively in nonrelativistic region
- NRQCD formalism to refine $O(\alpha_s \ln\beta)$ corrections

For differential cross-sections

Sumino etal(93), Fujii etal(94), Sumino,HY (10),,,

$$\frac{d\sigma}{dp_t^3} \propto \tilde{G}(\vec{p}, E_{t\bar{t}})$$

- LO in $(\alpha_s/\beta)^n$
- Smooth connection to perturbative region
- Possible to put on **event generators**

Top-Yukawa measurement

- Simulation analysis : (/s=500GeV with 1ab^{-1} and polarization (0.8, 0.3))
  - Fast detector sim. / cut-based analysis Yonamine etal. PRD84,014033
  - Full deector sim. / multivariate analysis T.Tanabe etal
- Cuts
  - Number of leptons (Isolation)
  - Event shape (Thrust)
  - Jet clustering (Durham exclusive jet algorithm)
  - B-tagging (4 b-tagged jets)
  - Top and Higgs mass reconstruction

- Jet clustering (Durham exclusive jet algorithm):

$$Y_{ij} = \frac{\max(E_i^2, E_j^2)(1-\cos\theta_{ij})}{E_{\mathrm{CM}}^2}$$

ij which gives the smallest Y are merged into one.
Continue until the number of jets is 6 or 8.

$Y_{5\to4(8\to7)} > Y_{\mathrm{cut}}$ is useful to discriminate signal from tt BG.

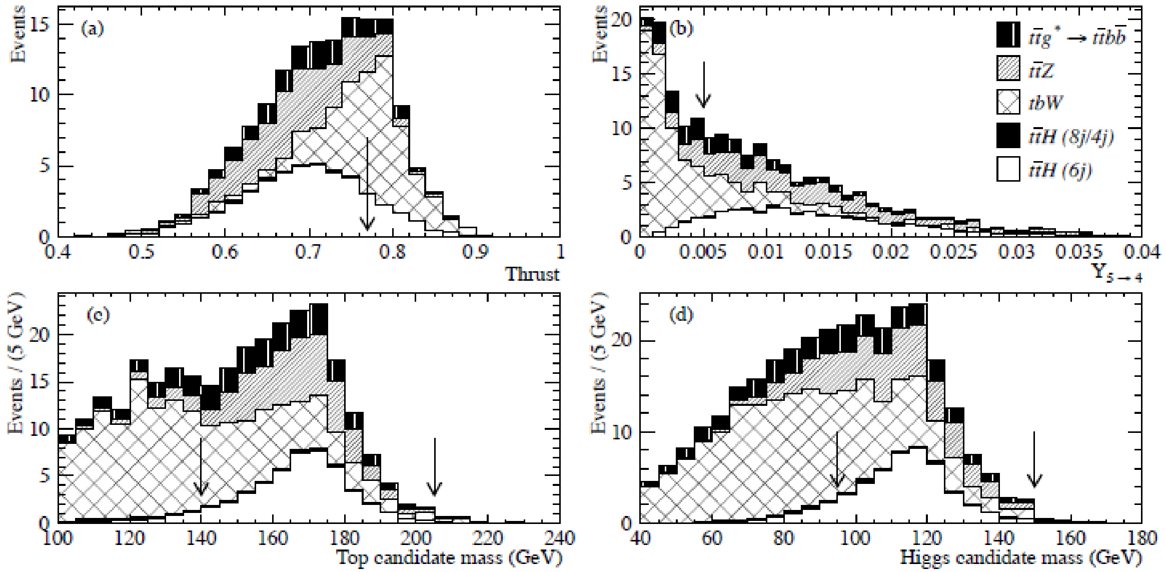
- Jet combination is fixed by minimizing chi-square;

$$\chi^2 = \frac{(m_{2j}-M_H)^2}{\sigma_H^2} + \frac{(m_{2j}-M_{W_1})^2}{\sigma_{W_1}^2} + \frac{(m_{3j}-M_{t_1})^2}{\sigma_{t_1}^2} + \left\{ \frac{(m_{2j}-M_{W_2})^2}{\sigma_{W_2}^2} + \frac{(m_{3j}-M_{t_2})^2}{\sigma_{t_2}^2} \right\}_{8j}$$

cut values

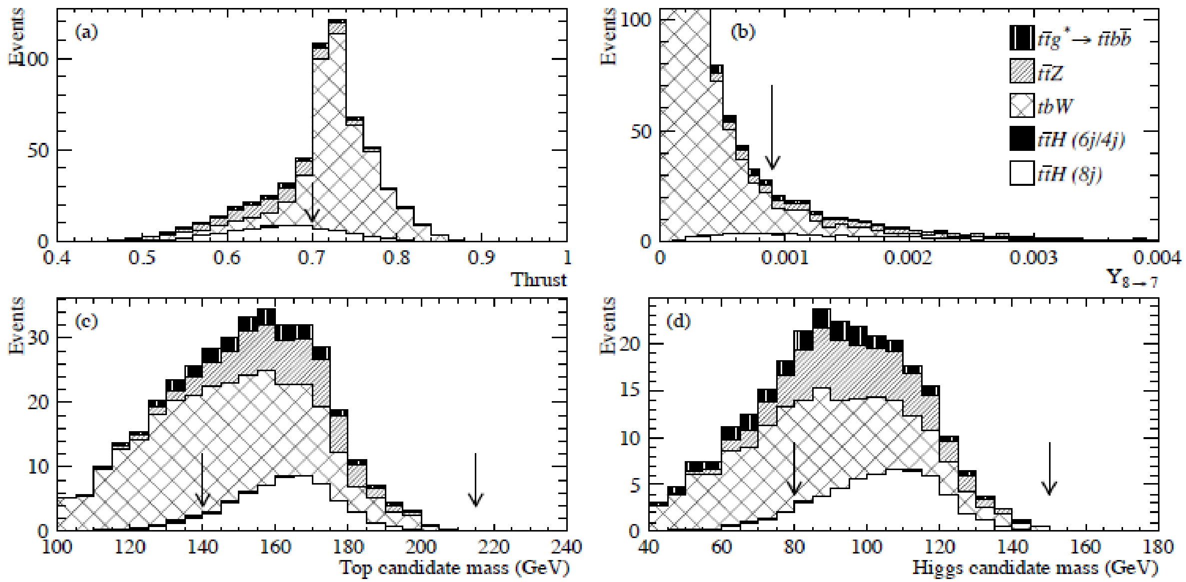
cut	6-jet + lepton	8-jet
number of isolated lepton	1	0
thrust	< 0.77	< 0.7
jet clustering	$Y_{5\text{->}4} > 0.005$	$Y_{8\text{->}7} > 0.00080$
b-tagging	4x b-jets	4x b-jets
top mass (GeV)	$140 < m_t < 205$	$140 < m_H < 215$
higgs mass (GeV)	$95 < m_t < 150$	$80 < m_H < 150$

- 6j + l



(a)
Events
Thrust
(b)
Events
$Y_{5 \to 4}$
$t\bar{t}g^* \to t\bar{t}b\bar{b}$
$t\bar{t}Z$
tbW
$t\bar{t}H$ (8j/4j)
$t\bar{t}H$ (6j)
(c)
Events / (5 GeV)
Top candidate mass (GeV)
(d)
Events / (5 GeV)
Higgs candidate mass (GeV)

- 8j



(a)
Events
Thrust
(b)
Events
$Y_{8 \to 7}$
$t\bar{t}g^* \to t\bar{t}b\bar{b}$
$t\bar{t}Z$
tbW
$t\bar{t}H$ (6j/4j)
$t\bar{t}H$ (8j)
(c)
Events
Top candidate mass (GeV)
(d)
Events
Higgs candidate mass (GeV)

- 6j + l

	$t\bar{t}H$ (6j)	$t\bar{t}H$ (8j)	$t\bar{t}H$ (4j)	tbW	$t\bar{t}Z$	$t\bar{t}g^*$ ($b\bar{b}$)
No cuts	282.3	289.5	68.3	980 738.5	2406.9	1159.6
Single isolated lepton	179.6	20.7	28.3	340 069.0	790.6	397.7
Thrust <0.77	145.7	18.5	19.2	144 999.0	616.7	266.0
$Y_{5\to 4} > 0.005$	125.5	16.6	9.2	12 297.7	416.2	113.7
b tagging	49.0	1.3	2.9	172.9	53.3	37.8
Mass cuts	39.5	1.2	0.4	23.0	33.9	13.2

- 8j

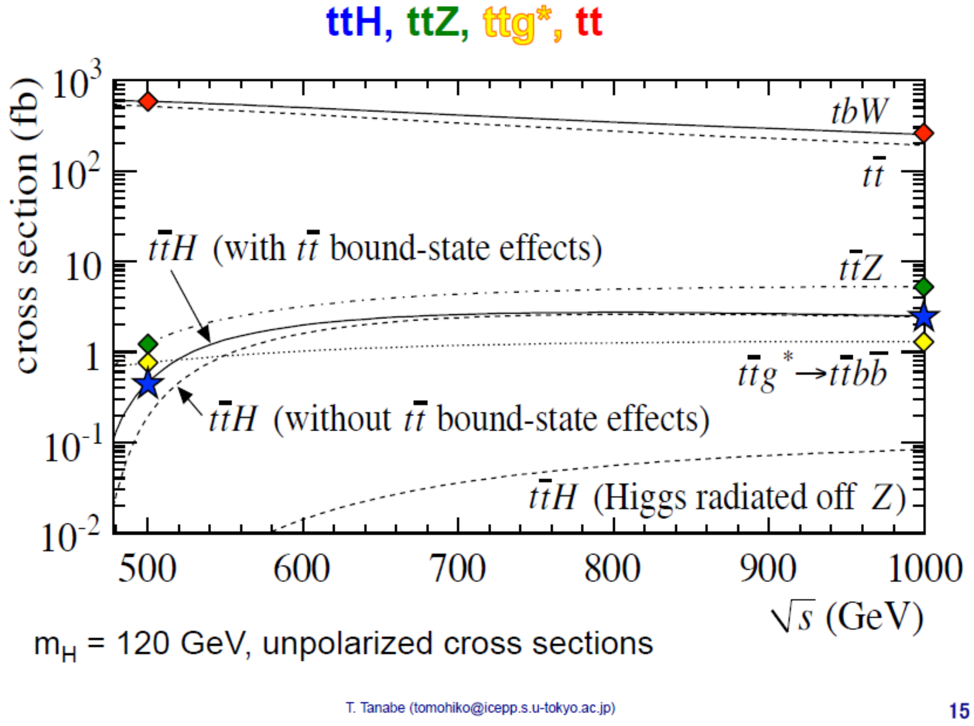
	$t\bar{t}H$ (8j)	$t\bar{t}H$ (6j)	$t\bar{t}H$ (4j)	tbW	$t\bar{t}Z$	$t\bar{t}g^*$ ($b\bar{b}$)
No cuts	289.5	282.3	68.3	980 738.5	2406.9	1159.6
Reject isolated leptons	266.3	85.6	6.6	589 716.0	1351.4	701.2
Thrust <0.7	167.7	44.0	2.7	107 227.0	818.0	311.5
$Y_{8\to 7} > 0.0009$	113.8	13.0	0.3	4048.1	349.6	67.1
b tagging	66.6	6.8	0.1	442.6	77.6	39.8
Mass cuts	50.1	0.4	0.0	75.6	47.6	14.1

3.7σ for both modes

/s = 1 TeV

- At 1TeV, signal increases (peak ~ 800GeV), but BG decrease
- Bound-state effects negligible
- ILD and SiD full simulation ongoing

expect to improve the accuracy



	$t\bar{t}h$ (4J)	$t\bar{t}h$ (6J)	$t\bar{t}h$ (8J)	$t\bar{t}h$ ($h \not\to b\bar{b}$)	$t\bar{t}Z$	$t\bar{t}b\bar{b}$	$t\bar{t}$	Sig.
No cuts	151.39	628.73	652.77	1046.10	5332.52	1434.53	306238.26	1.16
$N_{\rm iso} = 0$	20.87	261.17	647.92	556.71	3226.14	932.49	188911.38	1.47
$E_{\rm vis} > 650$ GeV	9.83	220.97	636.16	497.45	2743.54	849.34	157389.56	1.58
Thrust< 0.87	8.09	187.75	577.60	440.06	2219.68	540.88	46916.14	2.56
$Y_{78} > 0.0001$	3.65	143.55	549.52	415.51	1926.58	474.59	27472.09	3.12
$btag_4 > 0.38$	1.89	80.98	275.02	17.55	230.04	209.60	680.62	7.11
$\|\cos\theta_{\rm hel}\| < 0.9$	1.63	73.80	263.71	16.48	215.91	189.19	584.92	7.19
$m_t > 120$ GeV	1.50	68.09	255.38	15.58	207.81	178.53	530.93	7.20

- Cut-based ➞ Multivariate analysis:

	Statistical Significance	
	Cut-based	Multivariate
tth → bqqblvbb	**5.4**	**7.6**
tth → bqqbqqbb	**7.2**	**9.6**

- Summary of the Top-Yukawa measurements:

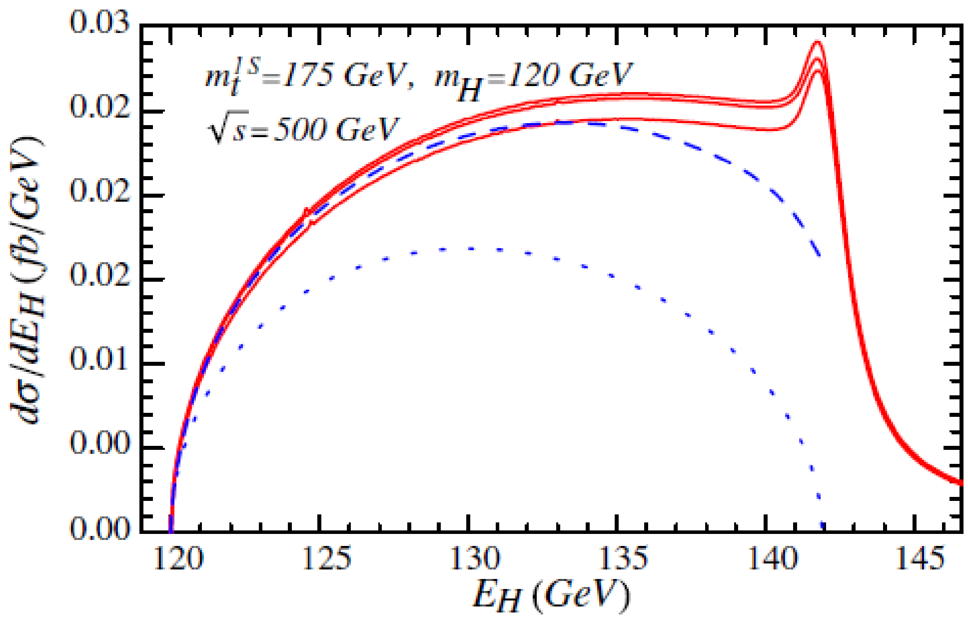
CM Energy	**500 GeV**	**1 TeV**	
Higgs mass	125 GeV	125 GeV	
Beam polarization	(−0.8, +0.3)	(−0.8, +0.2)	
Integrated Luminosity	1 ab^{-1}	1 ab^{-1}	
Detector Model	**ILD**	**ILD**	**SiD**
$\Delta y_t/y_t$	**11%**	**3.9%**	**4.0%**

Theoretical uncertainty

- Theoretical prediction has several % uncertainty due to the choice of renormalization scale.
- It is a common problem for ttbar threshold physics (NNLL)

  → needs new idea or higher order?

- Might be improved at 1TeV where fixed-order correction is enough.



Farrel, Hoang(05,06)

Summary

- Top-quark mass (or the Yukawa coupling) is an important input to find the evidence of the physics beyond the SM.
- Yukawa coupling of the top-quark can be directly measured at tth production process.
- At /s=500GeV, threshold correction enhance the signal by a factor of 2.
- The expected accuracy of the measurement at the ILC is

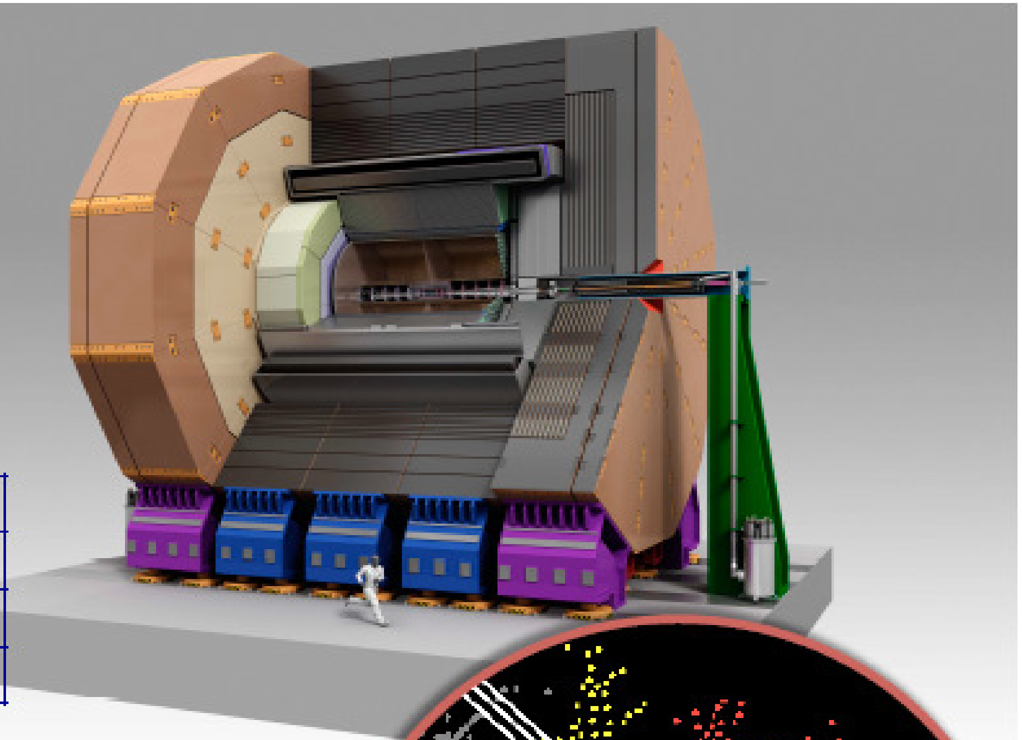
$$\frac{\Delta y_t}{y_t} \simeq 11\% \ @\sqrt{s} = 500 \ \mathrm{GeV}, 1\mathrm{ab}^{-1}$$

$$\frac{\Delta y_t}{y_t} \simeq 4\% \ @\sqrt{s} = 1 \ \mathrm{TeV}, 1\mathrm{ab}^{-1}$$

I thank T.Tanabe, R.Yonamine, K.Fujii,T.Price, N.Watson, H.Tabassam, V.Martin, P.Roloff, J.Strub, for providing their results shown in this talk.

ILD detector

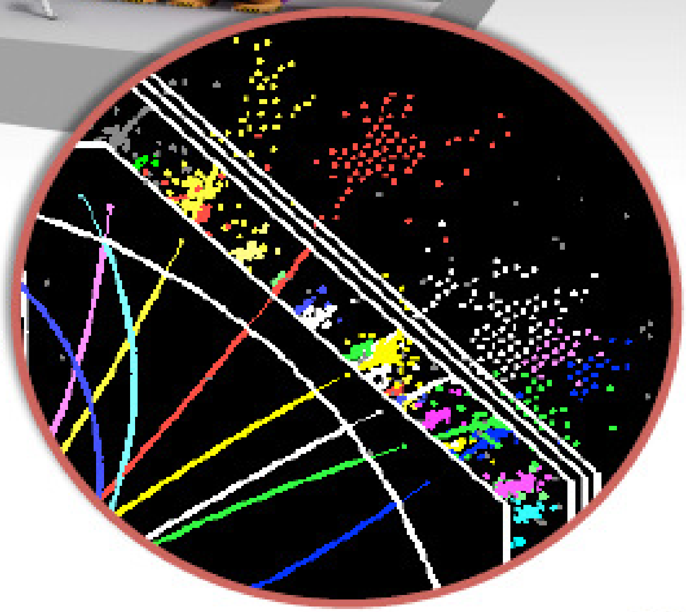
- **Vertex Detector:** pixel detectors & low material budget
- **Tracker:** low material budget
- **Calorimeters:** high granularity sensors



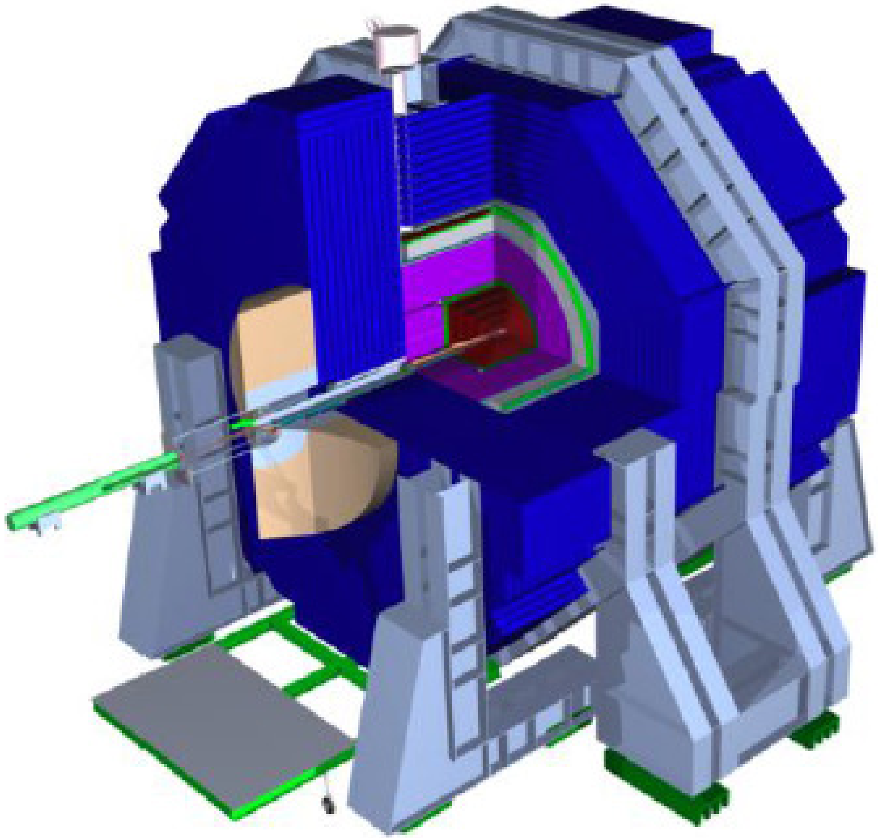
Sensor Size	**ILD**	**ATLAS**	**Ratio**
Vertex	5×5 mm^2	400×50 mm^2	x800
Tracker	1×6 mm^2	13 mm^2	x2.2
ECAL	5×5 mm^2 (Si)	39×39 mm^2	x61

Particle Flow Algorithm

Separate calorimeter clusters at particle level
→ use *best* energy measurement for *each* particle.
→ offers unprecedented **jet energy resolution**
Charged Tracks → Tracker
Photons → ECAL
Neutral Hadrons → HCAL

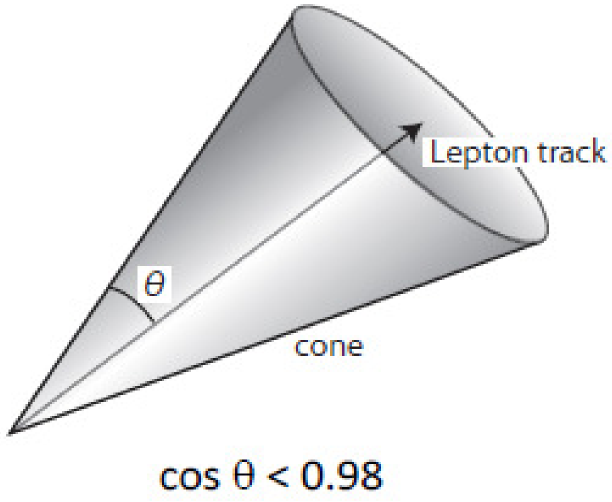


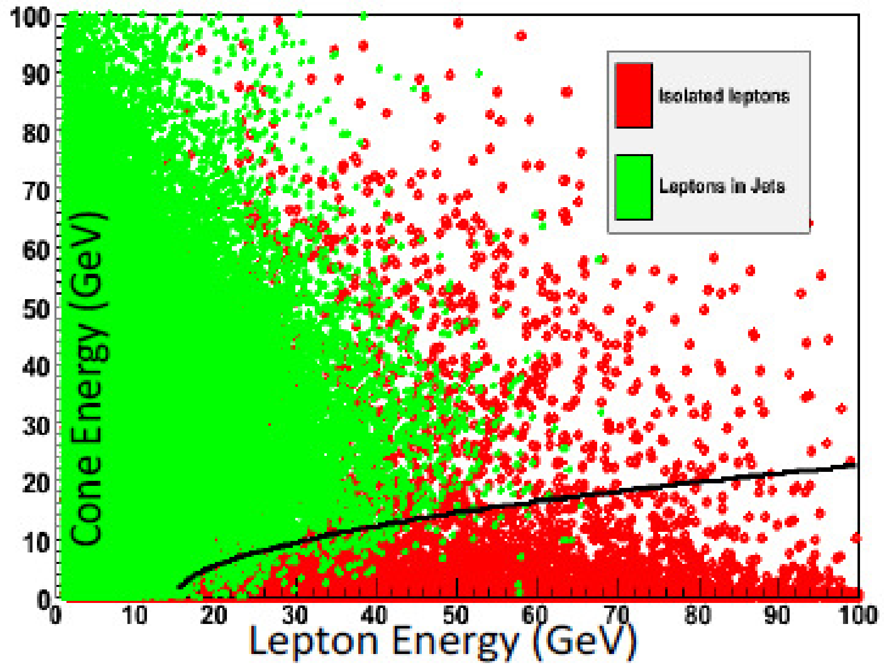
SiD detector:



lepton selection / veto

- lepton identification by MC information (assuming high efficiency & purity for E>15 GeV leptons)
- distinguish leptons inside a jet and those from top decay by summing the energy of the particles around the lepton
- 2-D selection (veto) of isolated leptons for the 6-jet + lepton analysis (8-jet analysis)





event shape

- use the thrust variable to discriminate signal from background

$$T = \max_{|\hat{n}|=1} \frac{\sum_i |\hat{n} \cdot \vec{p}_i|}{\sum_i |\vec{p}_i|}$$

jet clustering

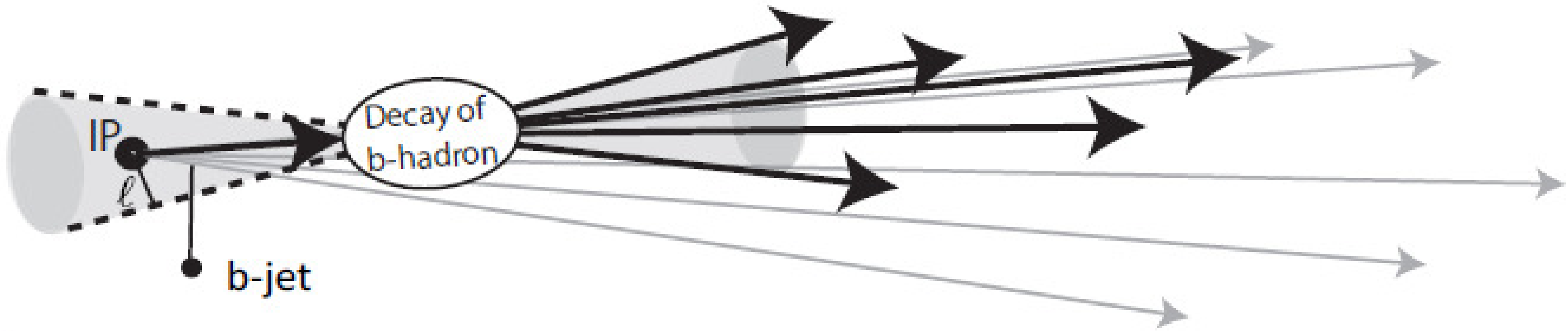
- we use the Durham jet clustering algorithm to force the event into the 6 (8) jet topology.

$$Y_{ij} = \frac{\max(E_i^2, E_j^2)(1 - \cos\theta_{ij})}{E_{\mathrm{CM}}^2}$$

b-tagging

- identify b-jets via their large impact parameter significance (IPS) of secondary tracks.
- b-tagging criteria:
  - **tight (6J+L)**: require 4 tracks with IPS >2.5
  - **tight (8J)**: require 2 tracks with IPS>3.0
    - efficiency: 47%, fake rate: c-jet 3.2%, uds-jet 0.1%
  - **loose**: require 2 tracks with IPS >2.0
    - efficiency: 80%, fake rate: c-jet 40%, uds-jet 0.5%
- event selection:
  - require at least 4 loose b
  - at least one tight b for Higgs candidate
  - one tight b for at least one top candidate

efficiency & fake rate estimated on Z->qq sample @ 91.2 GeV



jet combination

- choose the jet combination which is most consistent with the TTH mass hypothesis is chosen (minimize chi-squared):

$$\chi^2 = \frac{(m_{2j} - M_H)^2}{\sigma_H^2} + \frac{(m_{2j} - M_{W_1})^2}{\sigma_{W_1}^2} + \frac{(m_{3j} - M_{t_1})^2}{\sigma_{t_1}^2} + \left\{ \frac{(m_{2j} - M_{W_2})^2}{\sigma_{W_2}^2} + \frac{(m_{3j} - M_{t_2})^2}{\sigma_{t_2}^2} \right\}_{8j}$$